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Multi-Criteria Safety and Performance Assessment of Alternative Marine Fuels for Marine Applications

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The transition to alternative marine fuels introduces complex safety, environmental, and operational challenges that must be addressed to ensure reliable marine engine performance. This study applies a structured multi-criteria decision-making framework to evaluate candidate marine fuels, integrating stakeholder insights and technical data to inform risk-aware prioritization. Primary data was collected via structured questionnaires and analyzed using Analytical Hierarchy Process (AHP) and Evidential Reasoning (ER) methods, enabling systematic comparison of alternative fuels across safety, environmental, economic, and operational criteria. There is a focus on several alternative marine fuels, such as LNG, Liquid Hydrogen, Methanol, Ammonia, Biofuels and Hydrogen fuel Cells. Similarly, the analysis also assesses the various "colors" of Hydrogen against availability of technology, cost of production and emissions produced. The resulting prioritization provides a transparent, evidence-based basis for decision-making, highlighting fuels that minimize risk while maximizing reliability and performance. This work demonstrates the applicability of decision-theory methods to complex, safety-critical maritime systems, offering a framework to support strategic fuel transition while maintaining operational reliability and mitigating potential hazards.

Keywords: Alternative marine fuels; multi-criteria decision analysis; Risk assessment; Safety; Reliability; Analytical Hierarchy Process; Evidential Reasoning; Maritime systems.

1. Introduction

The global maritime industry accounts for approximately 90% of global goods transportation (OECD, 2023) and continues to expand annually. However, this growth brings significant environmental consequences. The combustion of marine fuel oils releases substantial quantities of CO_2, SO_x, NO_x, and particulate matter, contributing heavily to climate change and environmental degradation. As awareness of these impacts increases, governments and regulatory bodies are imposing stricter environmental standards on shipbuilders and operators. A central regulatory driver is the International Maritime Organization's 2050 GHG Strategy. The 2023 revision sets an enhanced ambition to achieve net-zero greenhouse gas emissions from international shipping by or around 2050, alongside commitments to increase the uptake of zero and near-zero GHG fuels by 2030, with indicative checkpoints for 2030 and 2040 (IMO, 2023). In response, global research and development efforts have intensified, focusing on alternative marine fuels such as ammonia, methane, and LNG. One comparatively underexplored alternative is Liquid Hydrogen (LH_2). While much hydrogen research concentrates on fuel cell technologies, less attention has been given to its viability as a primary fuel in marine diesel engines.

1.1. *Aim*

The aim of this investigation is to develop a method that facilitates direct comparison and evaluation of varying criteria, involving both qualitative and quantitative criteria, possibly under uncertainty, which would usually be incomparable directly in order to evaluate the safety and performance of various alternative Marine Fuels compared to Industry Standard HFO.

1.2. Objective

By utilizing a combination of Analytical Hierarchy Process (AHP) and the Evidential Reasoning (ER) Algorithm, non-quantitative data can be quantified and thus directly, numerically compared equally.

2. Marine Fuel Oils: Environmental Impact & Alternatives

2.1. *Current fuels*

Heavy Fuel Oils (HFO), the maritime industry standard, contain significant impurities — carbon, nitrogen, and sulphur — producing harmful emissions upon combustion. Shipping accounts for roughly 940 million tonnes of CO_2 annually (~2.5% of global emissions), rising 5% in 2021 alone (UKRI, 2021) (IEA, 2022). Atmospheric CO_2 has climbed from ~365ppm in 2002 to over 420ppm today (NASA, 2024).

Beyond CO_2, HFO combustion generates NOx: prolonged exposure to just 0.06–0.1ppm of NO_2 over two years causes acute respiratory disease, and shipping is responsible for 18–30% of global NO_2 emissions (SeaNews, 2019). Despite 0.5% sulphur content limits introduced in 2020 (IMO, 2020) shipping still contributes ~13% of global anthropogenic SO_2 emissions, causing respiratory damage and acid (Papadopoulos, Kourtelesis, Moschovi, Sakkas, & Yakoumis, 2022); (Queensland Gov, 2022).

2.2. *Alternative fuels*

2.2.1. *Ammonia*

Ammonia offers near-zero or zero carbon emissions on a tank-to-wake basis, and benefits from existing petrochemical and fertilizer infrastructure, including established handling guidance (EMSA, 2023). However, its toxicity — chiefly through NOx production — adds vessel design complexity and limits suitability to deep-sea cargo vessels rather than short-sea or inland routes. Cost is a major barrier: green ammonia costs roughly four times more per unit of energy than Very Low Sulphur Fuel Oil (~US$1,900 vs. $500/tonne equivalent) (Forbes, 2024). Its energy density is also approximately three times lower than standard fuels, requiring greater onboard storage, reducing cargo capacity, and increasing operational costs (Bureau Veritas, 2024).

2.2.2. *Liquified Natural Gas*

LNG can reduce NOx by up to 80% and nearly eliminate SOx and particulate emissions, achieving overall GHG reductions of ~23% with modern engines (DNV, 2024). It has the longest track record of any alternative, with trials dating to the 1970s, and global bunkering infrastructure is already expanding to accommodate it.

However, LNG's primary component — methane — traps 86 times more heat than CO_2 over 20 years, and the four-stroke engines most commonly used with LNG are the most prone to leakage (ICCT, 2020). Financially, widespread LNG adoption could cost the industry up to $850bn by 2030, though retrofitting LNG vessels to use hydrogen-based fuels could reduce losses to £113–185bn (UCL, 2022). Full lifecycle analyses suggest LNG's environmental benefits may even be negative compared to low-sulphur HFO, with the most cost-effective decarbonization pathway being electrification for short-sea shipping and hydrogen-derived fuels for deep-sea routes.

2.2.3. *Hydrogen Fuel Cells*

Hydrogen Fuel Cells (HFCs) generate electricity through electrochemical reactions with no combustion, emitting only water and heat. Proton Exchange Membrane Fuel Cells (PEMFCs) are a leading zero-emission option, and the technology integrates well with onboard battery systems and shore charging (ABB, 2024). Printed Circuit Board Fuel Cells (PCBFCs) have also been demonstrated in practice: in January 2023, Bramble Energy launched a 57ft narrowboat achieving ~600 miles of range on just 14kg of hydrogen, with potential CO_2 savings of 12 tonnes per vessel annually (Bramble Energy, 2024). The primary barrier is cost. A single PEMFC currently costs over £38/kW, with minimum installation costs of ~£192,500. The US Department of Energy is targeting a reduction to ~£27/kW, potentially lowering installation costs to ~£135,000 — excluding hydrogen storage (McKinlay, Turnock, & Hudson, 2021).

2.2.4. *Biofuels*

Biofuels are among the most immediately practical alternatives, compatible with existing engines requiring little or no modification, and capable of delivering an average GHG reduction of 72% compared to fossil fuels (Gartland & Pruyn, 2022); (EMSA, 2023). However, they cost two to three times more than standard marine fuels (€22–36/GJ), and the absence of standardized global supply infrastructure causes significant regional price volatility (Argus, 2023).

3. Law & Legislation

2023 saw significant regulatory developments around hydrogen as a marine fuel. In March, Lloyd's Register published regulations filling a gap in the IMO's IGF Code, covering bunkering, transport, and safety hazard identification for all hydrogen fuel types, coming into force on 01/07/2023 (Lloyd's Register, 2023). In June, the American Bureau of Shipping released guidance covering vessel design, fuel containment, bunkering, ventilation, safety systems, and crew training (Safety4Sea, 2023).

In July, the UK's Regulatory Horizons Council recommended a clearer regulatory framework for hydrogen vessels, aiming to provide shipbuilders with specialized guidance, speed up approvals, and boost investor and port owner confidence through improved governance of onshore hydrogen facilities (RHC UK Gov, 2023). In August, China's Classification Society issued its first Approval in Principle for a marine liquid hydrogen fuel supply system developed by Weishi Energy Technology Hebei, with further cooperation planned on hydrogen fuel cell approval — part of a broader pattern of Chinese investment in maritime hydrogen technology dating to 2020 (MarineLink, 2023).

Also in August, the Russian government partnered with Sistema PJSFC on hydrogen ship R&D, with Sitronics Electro planning a pilot hydrogen passenger vessel for September 2023. Russian institutions also struck international agreements, including a deal with Norwegian operator Edda Wind for four zero-emission Liquid Organic Hydrogen Carrier-based vessels due in 2025–26 (PortNews, 2023). A recurring concern highlighted was the lack of specialized infrastructure — widely considered the greatest barrier to hydrogen's viability as a mainstream marine fuel.

On the practical side, Powercell Group, E1 Marine, and RIX Industries successfully string-tested a 200kW hydrogen propulsion chain in Gothenburg, with results considered scalable to megawatt-level power generation for use across vessel types from inland push-boats to superyachts (Ship Technology, 2023).

4. Analytical Hierarchy Process and the Evidential Reasoning Algorithm

Analytical Hierarchy Process is a widely used multicriteria method in which an overall goal is broken down into a hierarchy of criteria; the Analytical Hierarchy Process method integrates the processes of rating the various alternative criteria and aggregating them to discern their relevance (Ramanathan, 2004). For this to be done, weights of importance of each factor must be calculated. This is done by pairwise comparison of the criteria, based on Saaty's method (Saaty, 1977), in which the importance of two comparable criteria is compared and then quantified via rating on a scale from 1 (Equal Importance) to 9 (Extreme importance), at its most basic. For a Matrix $A = [a_{ij}]$, (n x n) where a_{ij} is the preference of element i over j and $a_{ii} = 1$, shown in Equation 1:

$$GM_i = \left(\prod_{j=1}^{n} a_{ij} \right)^{1/n} \tag{1}$$

With the Principal/ Maximum Eigenvalue calculated from Equation 2:

$$Aw = \lambda_{max} w \tag{2}$$

Saaty introduced the Consistency Index (CI) and Consistency Ratio (CR) in order to ensure logical consistency between results, displayed in Equations 3 and 4:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

Wherein RI is the Random Index, being a predetermined CI for a randomly filled Matrix, according to Matrix Order, defined in Table 1.

Table 1: Random Index based on Matrix Order

Matrix Order (n)	2	3	4	5	6	7	8
RI	0	0.58	0.9	1.12	1.24	1.32	1.41

Evidential Reasoning is an MCDM analysis method which deals with both numerical data and qualitative information with uncertainty. The ER approach's algorithm is built upon from the framework and evidence combination rule of the

Dempster-Schafer Theory into a multileveled evaluation framework. Weight normalization factors and probability factors are used to further enhance the process of aggregating attributes with uncertainty, including the use of standardized distinct evaluation grades to increase the rationality of numerical answers calculated from degrees of belief and probability (Yang & Xu, 2002).

For a set of attributes $S(e_i)$ assessed to the evaluation grade H_n (H_{n+1} preferably), with the degree of belief β_n, for all values of n, for all specific attributes i $(i = 1, \dots, L)$, represented by Equation 5:

$$S(e_i) = \{(H_n, \beta_{n,i}),\ n = 1,\ \dots,\ N\} \qquad (5)$$
$$i = 1,\ \dots,\ L$$

Wherein $0 \leq \beta_{n,i}$, $\sum_{n=1}^{N} \beta_{n,i} \leq 1$ and denotes the degree of belief of an attribute given a specific evaluation grade: if the sum of the degrees of belief equates to 1 ($\sum_{n=1}^{N} \beta_{n,i} = 1$), Eq. 5 is satisfied.

Supposing the probability mass $m_{n,i}$ represents the degree to which the i^{th} basic attribute e_i supports the hypothesis that the attribute z is assessed to the n^{th} grade H_n, $m_{n,I}$ can therefore be represented by Equation 6:

$$m_{n,\,i} = \omega_i \beta_{n,\,i}\ ,\ n = 1,\ \dots,\ N \qquad (6)$$

Wherein ω is the Relative Weight of an Attribute, calculated via Pairwise Comparison, and thus the remaining probability mass which is unassigned to individual grades after all the basic attributes in a set have been assessed can be represented as $m_{H,\,i}$, displayed in Equation 7:

$$m_{H,\,i} = 1 - \sum_{n=1}^{N} m_{n,i} = 1 - \omega_i \sum_{n=1}^{N} \beta_{n,i} \qquad (7)$$

From this, both $m_{n,I(i)}$ and $m_{H,\,I(i)}$ can be determined through the combination of the basic probability masses $m_{n,i}$ and $m_{H,\,i}$ for all values of $n = 1,\ \dots,\ N, j = 1, \dots, i,$as shown in Equations 8 and 9:

$$m_{n,I(i+1)} = K_{I(i+1)}\big(m_{n,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1} + m_{H,I(i)} m_{n,i+1}\big) \qquad (8)$$
$$n = 1,\ \dots,\ N$$

$$m_{H,I(i+1)} = K_{I(i+1)} m_{H,I(i)} m_{H,i+1} \qquad (9)$$

Wherein $K_{I(i+1)}$ is a normalising factor so that $\sum_{n=1}^{N} m_{n,\,I(i+1)} + m_{H,\,I(i+1)} = 1$, and is defined by Equation 10:

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{j=1 \\ j \neq t}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1} \qquad (10)$$
$$i = 1,\ \dots,\ L-1$$

To satisfy, $m_{n,\,I(1)} = m_{n,1}$ for $n = 1,\ \dots,\ N$ and $m_{H,\,I(1)} = m_{H,1}$; basic attributes are numbered subjectively, so the results in $m_{n,\,I(L)}$ and $m_{H,\,I(L)}$ are not dependant on the order that the basic attributes are aggregated.

The combined Degree of Belief β_n, is defined by Equation 11:

$$\beta_n = \frac{m_{n,\,I(L)}}{1 - m_{H,\,I(L)}} \qquad (11)$$
$$n = 1, \dots,\ N,\ i = 1, \dots,\ L$$

β_H , the unassigned Degree of Belief for all unassigned to any individual evaluation grade after all the basic attributes have been properly assessed (displaying a degree of incompleteness) can be represented by Equation 12:

$$\beta_H = 1 - \sum_{n=1}^{N} \beta_n \qquad (12)$$

The utility of an evaluation grade H_n can be denoted as $u(H_n)$, and assuming there are five distinct evaluation grades, the utility of each respective evaluation grade must be determined satisfying $u(H_1) = 0$ and $u(H_5) = 1$. If no preference information is available, the values of $u(H_n)$ can be assumed to be equidistant, as shown in Equation 13:

$$\begin{aligned} u(H_n) = \{u(H_1) = 0,\ u(H_2) \\ = 0.25, \\ u(H_3) = 0.5,\ u(H_4) = 0.75, \\ u(H_5) = 1\} \end{aligned} \tag{13}$$

Ultimately, the estimated utility for the general and basic attributes given the set of evaluation grades, $S\big(z(e_i)\big)$, is thus defined by Equation 14:

$$u\Big(S\big(z(e_i)\big)\Big) = \sum_{n=1}^{N} u(H_n)\beta_n\,(e_i) \tag{14}$$

For this, $\beta_{n,i}(e_i)$ denotes the lower bound of the likelihood that e_i is assessed to a grade H_n; The corresponding upper bound is denoted as $\beta_n(e_i) + \beta_H(e_i)$ and is given the assumption that there is an incomplete Degree of Belief. When $\sum_{n=1}^{N} \beta_n = 1$, the utility estimation and a rank for each attribute can be determined (Yang & Xu, 2002).

5. Methodology and Results

Primary data gathering was done via a questionnaire circulated to members of both academia and industry.

The questionnaire was split into three sections. Section 1 covers participant information, consent, and demographics — including professional background, qualifications, and occupation — to identify whether responses differ between industry and academic participants.

Section 2 examines the suitability of various alternative marine fuels compared to Liquid Hydrogen across several criteria: hydrogen production methods, engine type (2-stroke vs. 4-stroke), voyage length, and vessel type. Participants rate each variable using five evaluation grades — Very Low (H1) through Very High (H5) — with responses expressed as Degrees of Belief (e.g., 50% Low, 50% Average), which together sum to 1. These ratings feed directly into the Evidential Reasoning (ER) algorithm. Suitability is assessed through a hierarchical structure: top-level criteria (Voyage Type, Engine Type, Life Cycle Impact) are broken into sub-criteria grouped by relevance. Life Cycle Impact, for instance, breaks down into Logistics, Service, and Manufacturing Process Impact, the last of which covers technology availability, production cost, and refinement emissions. Section 3 uses pairwise comparison matrices to determine the relative weight (ω) of each attribute within the hierarchy, where 0 ≤ ω ≤ 1. These weights are combined with the Section 2 belief degrees to complete the ER algorithm calculations, all in accordance with the Suitability Hierarchy shown in Figure 1.

Applying Saaty's Method and taking the geometric mean of ten participants' responses to

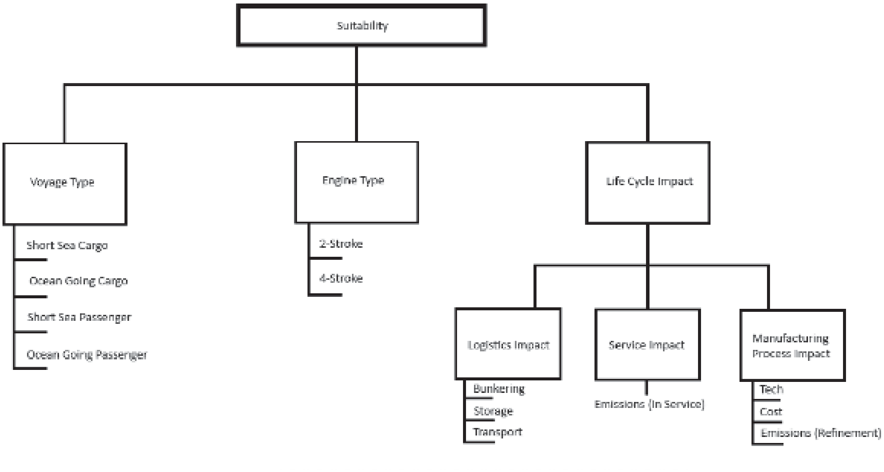

Figure 1: The Suitability Hierarchy

the subsection of the questionnaire which regarded the pairwise comparison of Life Cycle Impact, Engine Type Suitability and Voyage Type Suitability and using:

e_1 → Life Cycle Impact
e_2 → Engine Type Suitability
e_3 →Voyage Type Suitability

Then results are calculated as shown in Tables 2, 3 and 4.

Table 2: Pairwise Comparison Matrix

	e1	*e2*	*e3*
e1	1	0.438094	1.586157
e2	2.282617	1	2.599913
e3	0.630455	0.384628	1
SUM	3.913072	1.822722	5.18607

Table 3: Pairwise Comparison Matrix (cont.)

	e1	*e2*	*e3*	*WEIGHT*
e1	0.26	0.24	0.31	26.73%
e2	0.58	0.55	0.50	54.44%
e3	0.16	0.21	0.19	18.83%
SUM	1	1	1.00	1

Table 4: Pairwise Comparison Matrix (Final)

	e1	*e2*	*e3*	*SUM ROW*	*SUM WEIGHT*
e1	**0.27**	**0.24**	**0.30**	**0.80**	**3.010147**
e2	**0.61**	**0.54**	**0.49**	**1.64**	**3.019816**
e3	**0.17**	**0.21**	**0.19**	**0.57**	**3.00666**
				COUNT	**3**
				LAMBDA MAX	**3.012208**
				CI	**0.006104**
				CR	**0.0105**

As can be seen, the final CR value is well within the acceptable limit of 0.1, proving logical consistency between the participants' responses.

Replicating this method for all questions in Section 3 of the questionnaire gives the relative attribute weight values of:

$\omega_1 = 0.2673,\ \omega_2 = 0.5444,\ \omega_3 = 0.1883,$
$\omega_4 = 0.5499,\ \omega_5 = 0.3070,\ \omega_6 = 0.1430,$
$\omega_7 = 0.3672,\ \omega_8 = 0.1619,\ \omega_9 = 0.4709,$
$\omega_{10} = 0.3205,\ \omega_{11} = 0.2966, \omega_{12} = 0.3829,$
$\omega_{13} = 0.4599,\ \omega_{14} = 0.5401,\ \omega_{15} = 0.1684,$
$\omega_{16} = 0.5958, \omega_{17} = 0.0748,\ \omega_{18} = 0.1610$

As with the AHP calculations for discerning standardized ω_i weightings for all e_i attributes, the geometric mean can be calculated for the datasets of ten participants' responses to the Evaluation Grading section of the questionnaire in order to generate the average overall Suitability score for each Alternative Marine Fuel Source, for a final result shown in Table 5:

Table 5: Alternative Marine Fuel Options and their respective Suitability Scores

ALTERNATIVE	*SCORE*
L. Hydrogen	0.609935
HFC	0.472471
LNG	0.635917
Ammonia	0.437588
Methane	0.455911
Biofuels	0.457663

Assuming the same quality Hydrogen will be produced as a result of the respective refinement processes, and thus using the previously calculated values for ω_7, ω_8 and ω_9, scores for the overall Suitability of each specific "Colour" of Hydrogen were also calculated, as shown in Table 6:

Table 6: Different Hydrogen Sources/ Refinement Methods and their respective Suitability Scores

COLOUR	*SCORE*
Green	0.644950
Grey	0.524688
Blue	0.514704
Black	0.425502
Brown	0.478535

Thus, visualized rankings can be produced, as represented in Figures 2 and 3.

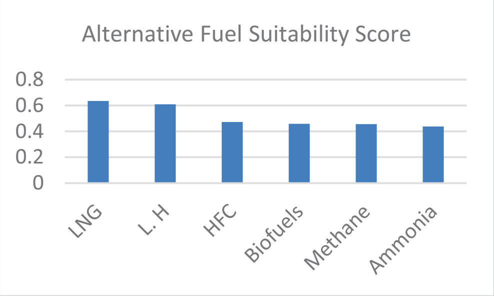

Figure 2: Alternative Fuel Suitability Scores

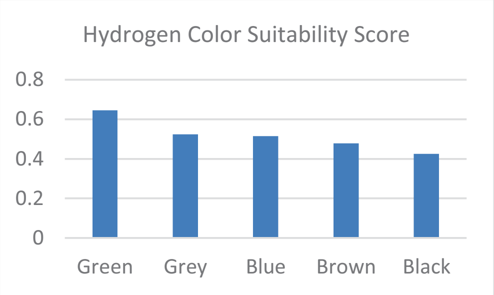

Figure 3: Hydrogen Color Suitability Score

5. Conclusions

As seen, the multi-criteria method of the combination of AHP and ER allows starkly different, usually incomparable criteria to be quantified through belief and thus makes the criteria directly numerically comparable, further allowing systematic prioritization of criteria, e.g., risk, and further in-depth analysis of any sub-category within any category. This method of analysis can be extrapolated to include any feasible number of varying criteria, especially in regards to safety, via the use of an extended Suitability Hierarchy (Fig. 1). In effect, this investigation at its core is a proof of concept that provides a highly adaptable framework for analysis through this methodology that facilitates further research in a multitude of settings.

Any results calculated via this methodology can be further developed in several ways. For instance, the results of this paper will be carried forth into an experimental method consisting of a combination of Finite Element Analysis, Computational Fluid Dynamics and Life Cycle Analysis to discern Liquid Hydrogen's suitability as an alternative Marine Fuel: the ranking of the Suitability Scores will directly inform the order of analysis and comparison; and the "Color"/ Refinement method of Liquid Hydrogen Production will inform which data will be used for Liquid Hydrogen during modelling.

Due to the limited data set taken from questionnaire responses, sufficient proof of a discrepancy in research direction between Academia and Industry could not be discerned at this stage.

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